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ORIGINAL INVESTIGATIONS

Electro-mechanical response times and rate of force development in males and females

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ABSTRACT

BELL, D.G. and I. JACOBS. Electro-mechanical response times and rate of force development in males and females. *Med. Sci. Sports Exerc.*, Vol. 18, No. 1, pp. 31–36, 1986. Muscle force development is influenced by both central (pre-motor end plate) and peripheral (post-motor end plate) components. Conflicting results are available concerning gender-related differences in the central component. This study compared males and females with regard to the following electro-mechanical response variables: total reaction time, pre-motor time, electro-mechanical delay, and the rate of force development during a maximal voluntary isometric contraction (MVC) of the elbow flexors. Forty-six males and 40 females performed MVCs against a bar attached to a force transducer. Subjects were instructed to attempt to flex the elbow with maximal force as rapidly as possible after perceiving a visual stimulus. Surface electromyographic activity was recorded from the biceps brachii and was sampled simultaneously with the force transducer data at 2 kHz and stored digitally. For data analyses the subjects were separated into four groups based on the force generated during the MVC: weak females, weak males, strong females, and strong males. Neither total reaction time nor pre-motor time was significantly different across groups. The electro-mechanical delay for both male groups was significantly shorter than for both female groups. Electro-mechanical delay was weakly, but significantly, correlated with rate of force development and maximum force. During a single MVC the times required to attain 25, 50, 75, and 100% MVC were similar in all groups. The results suggest that at least part of the gender difference in maximum strength may be due to differences in electro-mechanical response times.

STRENGTH, ELECTROMYOGRAPHY, MUSCLE

Muscle force generation during a maximum voluntary contraction (MVC) is dependent on both "central" and "peripheral" factors (15). The former includes the proportion of the available total motor unit pool which is recruited during contraction (14), motoneuron excitability (20), and the type of motor unit recruited during contraction (2). The peripheral factors include the cross-sectional area of the contracting muscle (7) and the biochemical and electrical events associated with the joining-sliding-relaxation of the contractile proteins.

These various factors result in several time delays during the course of muscle contraction and force generation (for a recent review see Ref. 23). Such delays include the interval between a stimulus and a change in electrical activity in skeletal muscle, and the delay between the change in electrical activity and actual force generation by the muscle (27). These time intervals will be collectively referred to as "electro-mechanical response times." Several investigators have reported measurements of electro-mechanical response times in different muscle groups in the same subject, as well as after fatigue (3,4,12,16,17,19,25).

These response times have been reported to be related to the rate of force development and maximal force generation during a MVC (25). Komi (10) has suggested that the lower rate of force development he observed in females compared to males may be the result of "structural differences between men and women in the muscle's elastic tissue." If such a difference exists it is tempting to speculate that it would also influence electro-mechanical response times because they have been linked to the time required to stretch the series elastic component (SEC) during a MVC (3). The difference in maximal strength between males and females, in addition to being associated with differences in muscle mass, should therefore also be associated with differences in electro-mechanical response times.

The purpose of the present study was to compare males and females with regard to electro-mechanical response times and rate of force development during isometric MVC of the elbow flexors. The hypothesis was that there would be a difference between genders and that within each gender the stronger subjects would have significantly faster rates of force development and different electromechanical transit times than weaker subjects.

METHODS

Subjects. Informed consent was obtained from 40 females and 46 males who volunteered to participate.

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Their age ranged from 19–46 yr. None of the subjects was an elite athlete, but their physical training history ranged from being sedentary to subjects who weight trained regularly.

Procedures. The subjects were asked to perform three maximum voluntary isometric contractions of the biceps brachii while holding a bar attached to a force transducer. They were told to keep the wrist joints fixed while contracting the biceps as quickly and strongly as possible after seeing a light stimlulus. The MVC was performed from a seated position with the upper arm perpendicular to the floor and to the forearm, which was at 90° to the point of force application on the bar held in both hands. Five submaximal contractions were performed before the MVCs. A 1-min rest interval intervened between successive MVCs.

Measurements. An electromyography (EMG) transducer, hybrid amplifier, and filter (Ampel model MV 9110-EMG) encased in silicon was strapped to the belly of the biceps brachii of the right arm. Some relevent characteristics of the amplifier and filter unit are as follows: bandwith B = 10 Hz–1 kHz, 24 dB/oct; input resistance $R > 10^{12}$ Ω; common mode rejection ratio $CMRR_{30Hz} > 100$ dB. The registered EMG signals were amplified 1,000 times and rectified. The force exerted by the subject was measured with a strain gauge (Lebow model 3169) which produced an electrical output. This output and the EMG signals were recorded on FM tape (HP model no. 3968A). A digital transient wave form recorder (Data Lab model no. DL2004) was used to capture the signals at a frequency of 2,000 samples·s^{-1}. The light stimulus, which signalled the subjects to perform the MVC, was used to trigger the start of the 1.9-s sampling interval. This time was sufficient to record both the rise and initial fall of force during the test. Computer software was used to determine the onset of EMG activity with an accuracy of one sample interval, equivalent to 0.5 ms. Another program was developed to determine the onset of force generation, defined as the first sample to exceed the base line force value by 5 N (26), as well as to select the times when force reached 25, 50, 75, and 100% of the maximum value. From the EMG and force recordings the following additional variables were determined: total reaction time (TRT), defined as the time from the light stimulus trigger until a force generation of 5 N above the base line value; pre-motor time (PMT), defined as the time from the light stimulus until the onset of EMG activity; and electromechanical delay (EMD), defined as the time between the onset of EMG activity and the onset of force generation. The data were transferred to a VAX 11/750 computer for statistical analysis using BMDP software (5).

Treatment of the data. Only data collected from the contraction which generated the greatest force were used for analysis. For this purpose the subjects were assigned to one of four groups according to sex and the median of the maximum absolute force values for each sex, i.e., weaker females, stronger females, weaker males, and stronger males. The data were analyzed using an analysis of variance and a Tukey Studentized Range post-hoc test of significance if the analysis of variance yielded a F-ratio significant at $P < 0.05$.

RESULTS

Males vs females. The differences between groups were not significant for PMT or TRT. Both male groups had shorter EMD times than both female groups (Table 1). Maximum absolute force generation during the MVC was significantly greater in both male groups; this difference was maintained even when force was expressed relative to body weight (Table 2). There were no differences in the times required to attain 25, 50, 75, and 100% of maximum force. This is shown in Figure 1, which demonstrates that the groups begin to diverge slightly in the "percentage of force vs time" relationship only after 75% of maximum force is reached. Figure 2 depicts absolute force plotted against time and shows that the rate of force development (RFD) for both male groups was 1.5–2.0 times greater than that of the females. This inter-gender difference was significant for absolute and relative (i.e., N·kg^{-1} body weight·s^{-1} RFD between 25–50% ($P < 0.01$) and between 50–75% maximum force ($P < 0.01$), but not between 75–100% maximum force (Table 3).

Stronger vs weaker. Maximum absolute force generation was significantly different between the stronger and weaker groups within each gender because this variable was the grouping factor. Force expressed rela-

TABLE 1. Electro-mechanical response times during a maximum voluntary isometric contraction of the elbow flexors.

	WF (N = 20)	SF (N = 20)	WM (N = 23)	SM (N = 23)
Total reaction time (ms)	196.0 ± 26.6	198.4 ± 32.0	188.5 ± 22.4	195.1 ± 29.6
Pre-motor time (ms)	162.2 ± 28.0	166.2 ± 32.8	161.8 ± 21.9	170.0 ± 24.9
Electro-mechanical delay (ms)	34.5 ± 16.3	32.2 ± 12.8	26.7 ± 10.3*	25.1 ± 10.4*

Values are mean ± SD.
* Significantly different from both female groups, $P < 0.01$.
WF, weaker females; SF, stronger females; WM, weaker males; SM, stronger males.

TABLE 2. Isometric force during a maximum voluntary contraction of the elbow flexors.

	WF (N = 20)	SF (N = 20)	WM (N = 23)	SM (N = 23)
Absolute force (N)	243.0 ± 36.5†	334.0 ± 42.3†	499.5 ± 67.4†	646.9 ± 48.9†
Relative force (N·kg^{-1})	4.08 ± 0.59†	5.34 ± 1.04†	6.63 ± 0.93†	7.92 ± 1.28†

Values are mean ± SD.
WF, weaker females; SF, stronger females; WM, weaker males; SM, stronger males.
† Different from all other groups, $P < 0.01$.

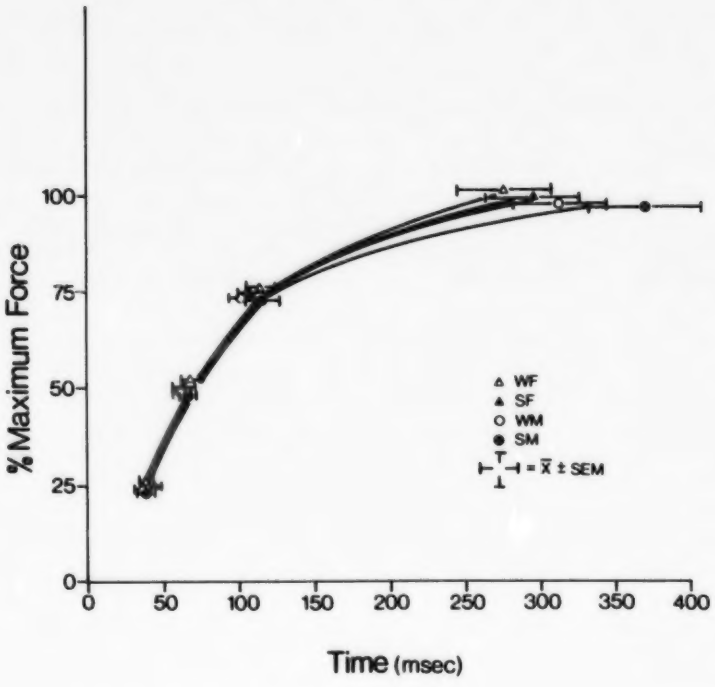

Figure 1—A comparison of the rate of force development expressed relative to maximum force generation during an isometric, maximum voluntary contraction. WF, weaker females; SF, stronger females; WM, weaker males; SM, stronger males. Bars, SD.

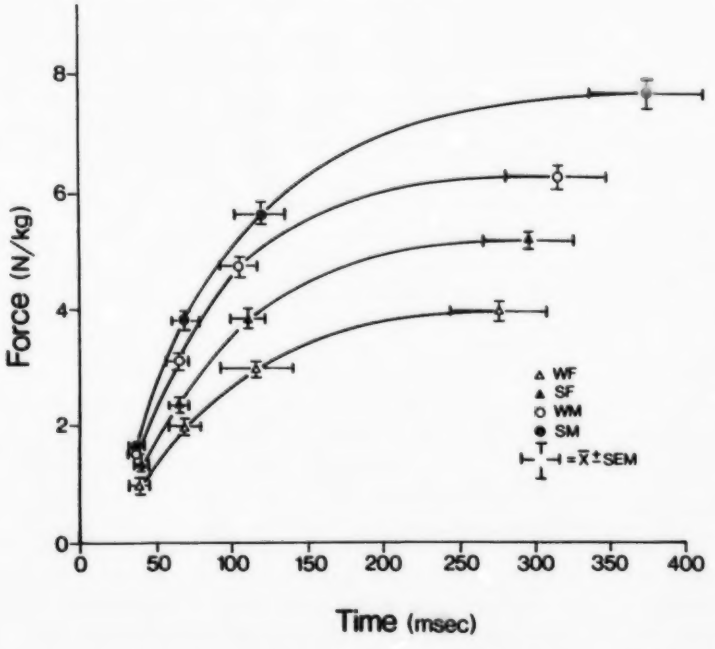

Figure 2—A group comparison of the rate of force development expressed relative to body weight. WF, weaker females; SF, stronger females; WM, weaker males; SM, stronger males. Bars, SD.

tive to body weight was also greater in each gender's stronger group (Table 2). There were no significant differences between the weaker and stronger groups within each gender for PMT, TRT, or EMD. EMD was significantly correlated with RFD between 25–50% maximum force ($r = -0.25$, $P < 0.05$), with RFD between 50–75% maximum force ($r = -0.23$, $P < 0.05$), and with maximum absolute force ($r = -0.32$, $P < 0.01$) when all subjects were considered as a single group.

DISCUSSION

The main finding in the present study was the significantly shorter EMD in the male subjects compared to the females. The finding of a gender difference in

TABLE 3. Rate of force development between 25–50, 50–75, and 75–100% of a MVC during isometric elbow flexion. The data are expressed as absolute values and relative to body weight.

	WF (N = 20)	SF (N = 20)	WM (N = 23)	SM (N = 23)
Absolute 25–50% MVC ($N \cdot ms^{-1}$)	2.46 ± 1.09	3.26 ± 0.88	5.27 ± 1.59†	6.18 ± 1.65†
Relative 25–50% MVC ($N \cdot kg^{-1} \cdot ms^{-1}$)	0.041 ± 0.019	0.052 ± 0.017	0.070 ± 0.023†	0.076 ± 0.023†
Absolute 50–75% MVC ($N \cdot ms^{-1}$)	1.66 ± 1.01	2.06 ± 0.56	3.40 ± 1.03*	3.86 ± 1.39*
Relative 50–75% MVC ($N \cdot kg^{-1} \cdot ms^{-1}$)	0.028 ± 0.018	0.033 ± 0.011	0.045 ± 0.014*	0.048 ± 0.023*
Absolute 75–100% MVC ($N \cdot ms^{-1}$)	0.54 ± 0.30	0.60 ± 0.30	1.23 ± 1.67	0.97 ± 0.77
Relative 75–100% MVC ($N \cdot kg^{-1} \cdot ms^{-1}$)	0.009 ± 0.005	0.010 ± 0.005	0.017 ± 0.024	0.012 ± 0.011

Values are mean ± SD.
WF, weaker females; SF, stronger females; WM, weaker males; SM, stronger males.
† Different from all other groups, $P < 0.01$.
* Different from both female groups, $P < 0.05$.

EMD stands in contrast to the study of Morris and Beaudet (17), who observed no difference between the sexes. Methodological differences may have contributed to the discrepant findings. Morris and Beaudet (17) determined the EMD manually from the EMG and force signals recorded at a paper speed of 200 $mm \cdot s^{-1}$ on a chart recorder. Measurement resolution was probably more sensitive and reliable in the present study, which employed much faster sampling rates of 2,000 samples$\cdot s^{-1}$ in addition to digitizing the data and using computer software to determine the onset of EMG and force generation.

The conflicting results of the present study and those of Morris and Beaudet (17) should also be considered in light of the inverse relationship between maximal isometric strength and EMD time demonstrated by Viitisalo and Komi (25). This relationship was also observed in the present study, although it should be noted that it was weak but statistically significant. A smaller difference in strength between the male and female groups in the study of Morris and Beaudet (17) compared to the present study could partially explain the different findings. Unfortunately, no force data are presented in the former study for comparison.

Cavanagh and Komi (3) suggested that the major portion of the measured EMD is used to stretch the SEC within the musculature. This was supported by their demonstration that when an MVC is performed during a concentric movement, EMD is longer than during an eccentric contraction, when the muscle is pre-stretched prior to the MVC. Based on this theory, one can speculate that the SEC in the males' muscle in the present study was more resistant to stretching than was the case for the females, thereby shortening the EMD in the male group. Such a structural difference in tissue elasticity was proposed by Komi (10) to explain the almost twofold longer time required by females to attain 70% MVC than males (11). The stiffer muscle in the males could be attributed to their prior activity history which, in our society, would probably include more daily activities likely to elicit a strength training effect than would be the case for females (28). This explanation implies that EMD is a peripherally mediated factor affecting muscle force generation because the SEC is located distal to the motor end plate.

TABLE 4. Comparison of published values for TRT and EMD. All times are in ms.

Reference No.	Joint	Movement	Stimulus	TRT	EMD
27	Finger	Concentric extension	Sound	173.9	64.6
21	Fingers	Isometric flexion	Sound	140.3	34.5
25	Knee	Isometric extension	Sound	161.4	38.3
21	Fingers	Isometric flexion	Light	231.8	39.2
12	Knee	Concentric extension	Light	246.0	
22	Elbow	Concentric flexion	Light	201.5	
4	Knee	Concentric extension	Light	210.3	86.8
				221.3	87.0
3	Elbow	Eccentric	Light		49.4
	Elbow	Isometric	Light		53.9
	Elbow	Concentric	Light		55.4
Present	Elbow	Isometric flexion	Light	194.3	29.3

The gender-related difference in EMD might also be partially explained if there were extreme differences in predominant muscle fiber type of the elbow flexors. EMD time has been shown to be inversely related to the proportion of fast twitch (FT) fibers in the contracting musculature (9,25). Further support for the importance of muscle quality with regard to EMD was provided by Norman and Komi (19), who observed a shorter EMD for contraction with the triceps brachii, containing relatively more FT fibers (8), than for contraction with the biceps brachii muscle. Even if the muscle fiber type distribution was similar in the elbow flexors of both sexes, central factors could affect EMD if the females were unable to recruit all available motor units. In the biceps, additional motor units are progressively recruited throughout the force range up to 100% MVC (13), implying that FT motor unit recruitment is exceedingly important in order to produce relatively high forces because they are generally recruited after recruitment of the slow twitch motor unit pool (6). An inability to recruit the available units would not only decrease the maximal force generation (1) but also could result in a longer EMD than if all the available FT motor units were recruited (25). There is, however, no direct evidence to support this contention, and the results of the present study are not sufficient to determine if the observed differences in EMD were centrally or peripherally mediated.

No differences were evident between the groups in the time required to attain various percentages of their MVC force. Komi and Karlsson (11) found that female subjects required about twice as much time as males to attain 70% MVC. In contrast, Morris et al. (18) observed that times to 10, 25, 50, 75, and 100% MVC were faster in females than in male subjects. Differences in the physical activity histories, e.g., the extent of familiarity with performing MVCs, between the subjects in the various studies probably contributes to the conflicting findings.

Since times to 100% MVC were similar across groups, the RFD was expected to be greater in the stronger groups. This was the case when the males were compared to the females, but no differences were evident within each gender when the weaker and stronger subjects were compared. Viitasalo and Komi (24) also reported a slower RFD in female than in male cross-country skiers. This difference in RFD could be attributed, once again, to an inability to recruit available motor units or to there being fewer FT units in the contracting musculature (24).

In spite of the shorter EMD in the male groups, the mean value for TRT was similar in all groups because of the large variation in PMT values. Table 4 presents the mean values for the various electro-mechanical response times measured in the present study, as well as other published data. From this table it is evident that responses to auditory stimuli are faster than to visual stimuli which were used in the present study. The TRT values in the present study are shorter than other studies in which a visual stimulus was used to trigger the beginning of contraction (4,11,21,22). In these other studies an incandescent light bulb was used as the visual stimulus; such a light causes a 25–100-ms delay from the time the electrical circuit is closed until the bulb filament is lighted and can be perceived. In the present study a light emitting diode was used, which reduced this delay to less than the sampling frequency of 0.5 ms.

In summary, the present study demonstrated that EMD was significantly shorter in male subjects than in females and that this was accompanied by a greater rate of absolute force development during an isometric MVC in the males. In light of the inverse relationship between maximal voluntary isometric force production and EMD time, the results suggest that at least part of the difference between males and females in strength may be associated with differences in electro-mechanical response times. It should be noted that the present data are descriptive in nature and cannot explain the mechanism behind the "EMD-strength" correlation reported previously (25) and confirmed in the present study. An alternate interpretation of the different EMD times could be that they are indirectly related to gender and are simply a function of the strength differences among the four groups.

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